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A literature survey on measuring energy usage for miscellaneous electric loads in offices and commercial buildings

Andreas Kamilaris*, Balaji Kalluri, Sekhar Kondepudi, Tham Kwok Wai

Department of Building, National University of Singapore, Singapore

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ABSTRACT

This paper presents the current state of the art regarding work performed related to the electric energy consumption for Information and Communication Technologies (ICTs) and Miscellaneous Electric Loads (MELs), in office and commercial buildings. Techniques used for measuring the energy consumption of office plug loads, and efforts for saving energy by using this equipment more rationally and efficiently are identified and categorized. Popular methods and techniques for energy metering are discussed, together with efforts to classify and benchmark office equipment. Our study reveals that many issues are still open in this domain, including more accurate, diverse and meaningful energy audits for longer time periods, taking into account device profiles, occupant behavior and environmental context. Finally, there is a need for a global consensus on benchmarking and performance metrics, as well as a need for a coordinated worldwide activity for gathering, sharing, analyzing, visualizing and exposing all the silos of information relating to plug loads in offices and commercial buildings.

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* Corresponding author.
E-mail address: kami@nus.edu.sg (A. Kamilaris).

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1. Introduction

It has been stated that "*if putting a man on moon was one of the greatest challenges the 20th century faced, tackling climate change is a much bigger challenge that we in the 21st century are confronted with*" [1]. Electricity represents 40% of the total energy used in the U.S. [2], primarily being used for heating, cooling, lighting and powering appliances across all sectors – residential, commercial and industrial. The importance of energy efficiency for computing equipment in offices is becoming more relevant. If one considers the total cost of ownership (TCO), while manufacturers have continuously driven down the capital cost of such equipment, the operational costs (i.e. electric consumption) have been rising [3–6].

In 2008, commercial buildings consumed about 20% of total U. S. primary energy (18.3 Quadrillion BTUs per year) [7], a figure projected to grow by 36% at 2030 (from 2008) [8]. Unlike the residential sector with 115 million households (in 2009), the commercial sectors' energy consumption is concentrated in 5 million buildings. As a result, energy use intensity (energy per unit floor area per year) is the greatest in commercial buildings when compared to residential or industrial.

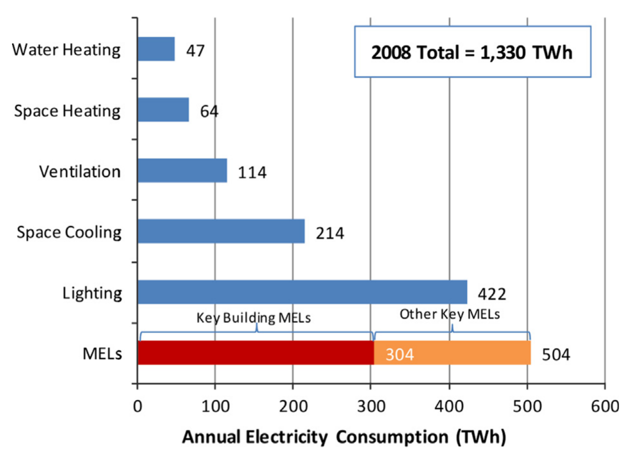

Fig. 1. Annual energy consumption of MELs in relation to other loads (Source: [7]).

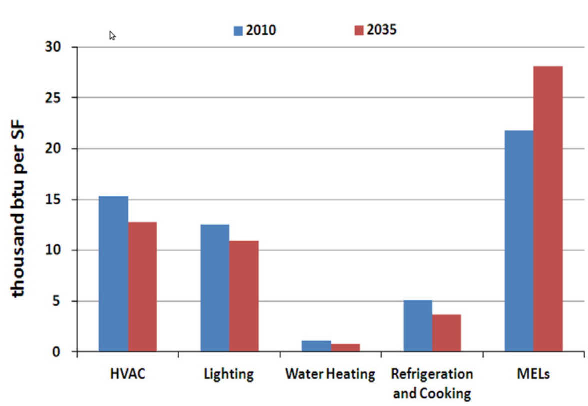

Fig. 2. Projection of energy demand in 2010 vs 2035 (Source: [14]).

1.1. Miscellaneous electric loads

Miscellaneous electric loads (MELs) are defined as non-main commercial building electric loads, that is, all electric loads except those related to main systems for heating, cooling and ventilation [7]. MELs are also described as electricity-consuming loads that do not fall under conventional end uses, such as lighting, HVAC and refrigeration [9]. Key types include consumer electronics and recent evidence suggests that MELs contribute significantly to the building's energy load.

MELs account for more than 20% of primary energy used in commercial buildings, and this percentage is projected to increase by 40% in the next 20 years [8,10]. This has made MELs one of the fastest growing load categories [11]. This growth relates to the fact that PCs and other office devices are penetrating office buildings, creating a large installed base of computing equipment. In 2001, yearly power consumption of office equipment accounted to 2% of the total electricity use in U.S. [12], while, as Fig. 1 shows, MELs consume more electricity than any of the traditional building main loads.

MELs constitute the large majority of office equipment, while an important part of them is about plug loads related to Information and Communication Technologies (ICTs), such as desktops, monitors, and printers. A study measuring consumption in a controlled environment at the University of California, San Diego [13], revealed that ICTs accounts for more than 70% of the MELs-based electricity load, being 50% of the total load during peak hours, reaching almost 80% during off-peak hours.

Traditional end uses are projected to decrease or remain the same from 2010 to 2035, while energy intensity of MELs is projected to increase[1] [14], as displayed in Fig. 2.

This is partly because research on energy efficiency and deployments has focused on the traditional end uses in the past two decades. At the same time, the rapid market penetration of consumer electronics has expanded the MELs category significantly, however, the energy use and reduction strategies for MELs have so far received little attention.

Reducing plug load consumption in offices could be a potential measure to improve net-zero energy buildings [15]. While tight regulation and efficiency have pulled down lighting and HVAC loads down to 50%, consumption from unregulated plug loads has been increasing. MELs are evolving into dominant loads, and this creates a threat in achieving net-zero energy [14].

[1] This study has been performed specifically for Germany. For different climatic conditions, this projection could be different.

This underestimation of the contribution of MELs in overall consumption is also revealed by a report by Fujitsu [16], claiming that most organizations do not seem to have a bill of energy consumed through the use of Information Technology (IT) and very rarely the organizations include ICT loads in IT department's own operating budget. This means IT managers do not know how much energy they are consuming hence they cannot know the scale of emissions they are responsible for. The maturity level in green ICTs is low and it is attributed to the fact of lack of maturity in green ICT policies, practices and technologies in most of the predominant ICT-using countries.

Except from the increase in energy consumption, MELs also affect the power quality of the electric network, mainly by inserting harmonics and transients in the voltage signal [17,18]. Although this is not the main focus of this paper, it should be considered by the readers as another important issue affecting the power quality inside an organization.

These studies and findings indicate that MELs represent an important, not well-studied category of energy consumption sources. Mitigating their energy consumption requires more transparency [19], and a consistent way to find out where the consumption is really coming from, measuring in detail its energy footprint. Hence, it is interesting to identify and present the state of the art regarding efforts to characterize, analyze, measure and reduce the consumption of MELs.

This is the actual contribution of this survey paper, discussing possible taxonomies of MELs and potential benchmarks of their performance (Sections 3 and 4), describing devices and techniques used for energy metering (Sections 5 and 6), presenting works performed on energy audits of office equipment in commercial buildings (Section 7), and identifying initiatives for saving energy by using plug loads more rationally and efficiently (Section 8). Finally, we list open issues for future work (Section 9) and conclude the paper (Section 10).

This survey paper constitutes the first attempt, to our knowledge, for studying the role and impact of plug loads in offices and commercial buildings, in terms of energy consumption.

2. Methodology

Before describing the important work in the field, we need to explain our methodology in collecting this information, which involved three steps:

1. Collection of the state of the art work.
2. Clustering of related work.
3. Analysis of related work.

In the first step, we performed a keyword-based search for papers in well-known scientific databases (e.g. IEEE Xplore, ACM, DBLP, ScienceDirect, CiteSeerX) and also in search engines. We used keywords such as “plug loads”, “miscellaneous electric loads”, “ICT equipment”, “offices”, “commercial buildings” and combinations of them. After identifying 84 papers with this approach, we performed a depth search on their most relevant references, increasing our database to 208 papers. Then, we examined technical reports, case studies and publications produced and developed by large, well-known international organizations operating in the field of energy in commercial buildings (e.g. EPRI, ASHRAE, NBI, PIER, IEA, GSA), increasing our bibliography to 260 papers/reports.

In the second step, we categorized related work in clusters according to their topic. At first, we created six large clusters: taxonomy, benchmarks/metrics, energy metering hardware, energy monitoring techniques, energy audits in offices, and approaches for energy savings in commercial buildings. Then, at each cluster we created smaller sub-clusters, for better categorization. For example, approaches for energy savings were divided into four sub-clusters: hardware techniques, software methods, suggestions/advice, and practices for affecting the occupants.

In the final step, we examined each cluster one by one, studying and analyzing each paper separately, recording its summary, its contribution and impact to the community, and its overall novelty and importance. Hence, after this procedure, we selected only the 5–8 more important papers per sub-cluster or the 15–20 more significant work per cluster. Through this approach, we collected 115 papers/reports, which we studied more extensively. The rest of this survey is based on the analysis performed on these documents, organized in the aforementioned clusters, composing the main sections of the survey.

3. Taxonomy of plug load-based equipment

Energy use of plug load-based office devices is dependent on their power consumption characteristics, built-in power management (PM) features (e.g. low-power modes) and user interaction. Thus, it is important to categorize these devices according to their usage and consumption patterns. Appropriate categorization and taxonomy would facilitate energy audits, energy wastage analysis and predictions of future consumption, helping to identify trends in office equipment's usage patterns.

At first, Kawamoto et al. [12] tried to classify energy use by office and network equipment, ranking office equipment into 11 types (portable and desktop computer, minicomputer, server, mainframe, terminal, display, laser and inkjet printer, copier, and fax) and network equipment into 6 types (LAN and WAN router and switch, access device, hub). As a metric, they used the unit energy consumption (UEC), defined as the average annual energy used by each piece of equipment. In parallel, Cremer et al. [14] recorded the stock and energy demand of modern ICT appliances in offices in Germany. At the appliance level, their equation for calculating consumption was the following:

$$\begin{aligned}&\mathit{Appliance\ Energy\ Consumption}\\&\quad=(\mathit{Normal\ power} * \mathit{time\ of\ use})\\&\qquad+(\mathit{Standby\ power} * \mathit{time\ of\ use})\\&\qquad+(\mathit{Off-mode\ power} * \mathit{time\ of\ use})\end{aligned}\tag{1}$$

Then, Roberson et al. [20] provided data on numbers and types of office equipment, while Nordman and Sanchez [21] categorized all electronic products whose primary function is information, providing a taxonomy of product types, covering both residential and commercial consumption. The overall structure of their taxonomy is listed in Table 1. Their aim was to provide definitions for key terms and concepts with the intent that future work could be more consistently reported and interpreted. Their taxonomy consisted of three levels: end use, category and product type. End use was further divided into three levels: electronics, miscellaneous and traditional.

As this taxonomy shows, traditional end use has received the main attentions for energy savings up to now. However, as we mentioned before, recent studies indicate that electronics constitute a significant portion of the overall consumption in commercial spaces, hindering the efforts for net-zero energy [7,14]. Finally, a more recent study [7] describes various commercial building types by which key MELs are categorized, together with an assessment of their energy consumption and an estimate of technical energy savings potential.

In regard to taxonomy, the work of Nordman and Sanchez [21] is pioneering in the field, trying to generalize across countries and building types. Although related work has recorded sufficiently the ICT equipment in offices, the fact that electronics are changing in a

Table 1
Overall structure of the taxonomy by Nordman and Sanchez (Source: [21]).

End use	Categories
Electronics	Audio, cash exchange, computer, display, imaging, networking, peripherals, security, set-top, telephony, video
Miscellaneous	Business equipment, commercial kitchen equipment, electric housewares, hobby/leisure, infrastructure, major appliances, medical (lab, exam, and specialty), other, outdoor appliances, personal care, power, transportation, utility, water heating
Traditional	HVAC, lighting, major appliance, water heating

very fast pace suggests that an evolving and dynamic taxonomy needs to be defined, which could be updated frequently maintaining its structure, being able to *absorb* new devices appearing at the market.

4. Benchmarking for office equipment

It is difficult to measure how green or sustainable is a building, based on the energy use of its plug loads. In this section, we present some benchmarks and key performance indicators (KPIs) proposed towards achieving this goal. At first, we discuss general benchmarks for office equipment-related green buildings, and then focus on metrics related to MELs.

4.1. Benchmarks for green buildings

The National Australian Built Environment Rating System (NABERS) [22] is a performance-based environmental impact rating system for existing buildings. It has various ratings, including the “Energy for office equipment load assessment” and the “Energy for data centers”. The former considers ICT-based data (e.g. number of computers, hours of occupancy) and the latter benchmark guidelines for facilities.

Europe's BRE Environmental Assessment Method (BREEAM) [23] offers credits for use of advanced building energy management systems, choice of plug load equipments with energy efficiency labeling (see Section 4.2), and provision for automatic power-down of devices when not in use. Singapore's Building and Construction Authority (BCA) Green Mark scheme [24] gives credits for use of energy efficiency products that are certified by approved local certification bodies. The Leadership in Energy and Environmental Design (LEED) rating system [25] is another benchmark, developed by the U.S. Green Building Council, defining various ratings, customized to different project sizes and types. Energy Usage Intensity (EUI) was selected as a metric in a study of 121 LEED-certified buildings in the U.S. [26] measuring 62 kBtu/ft^2 as median EUI.

Odyssee was a project within Intelligent Energy Europe, which produced two databases: one on energy efficiency data and indicators, and another on policy measures [27]. The databases are continually updated and access is free to registered users. ENERGY STAR Portfolio Manager [28] is an online tool for benchmarking the performance of one building or a whole portfolio of buildings.

4.2. Energy efficiency of plug loads

ENERGY STAR [29], a voluntary partnership between the U.S. Department of Energy (U.S. DoE), the U.S. Environmental Protection Agency (U.S. EPA) and the industry, has as primary goal to prevent air pollution by expanding the market for energy-efficient products through the application of the ENERGY STAR label. The label is a mechanism that allows consumers to easily identify products saving energy and money, mainly through proper PM [30].

The LEED-CI benchmark contains the Energy and Atmosphere Credit 1.4 (EAc1.4), dedicated to ENERGY-STAR eligible equipment being installed [25]. A recent study collecting data related to plug load energy use from 660 LEED-CI projects found that the median percentage of ENERGY STAR-rated devices per eligible equipment was 93% [31].

Similar to ENERGY STAR, the European Commission has developed the “EU Standby Initiative” [32], to improve the energy efficiency of electric equipment while either off or in standby mode. European Commission has also defined “Code of Conduct”, a mechanism to initiate and develop policies to improve energy efficiency. Additionally, the European “Energy-related Products Directive” [33] is a framework for setting eco-design requirements for energy-related products and the “TCO Certification” [34] is designed to ensure that ICT equipment has a high degree of usability for the end user, keeping environmental impact to a minimum.

The ASHRAE MELs Usage Factor [35,36] is defined as the ratio of measured wattage at nominal operating conditions to nameplate rating. It is estimated for PCs to be 0.85, while for other office equipment between 0.8 and 1.0, except from copiers where it is 0.5. Finally, Bristol City Council [37] developed a methodology for any city/region to assess its non-domestic ICT-related CO_2 emissions, calculating the annual energy consumption for each hardware unit using the following equations:

$$\begin{aligned} &\textit{Annual ICT Energy Consumption (per hardware unit)} \\ &\quad = (\textit{No. employees}) * (\textit{No. hardware units per employee}) \\ &\qquad * (\textit{Hardware unit energy consumption per year}) \end{aligned} \tag{2}$$

$$\begin{aligned} &\textit{Hardware unit energy consumption per year} \\ &\quad = (\textit{Energy Consumption}) * (\textit{Usage in various OS modes}) \end{aligned} \tag{3}$$

4.3. Plug load density

A report by New Buildings Institute (NBI) [38] defines some KPIs for commercial building energy use, such as occupant plug load and average plug load energy use rate. These KPIs have been calculated based on the results from two office buildings outfitted with system-level metering, using methods such as whole-building energy analysis, detailed sensitivity analysis modeling, and site visits and assessments.

A study by ASHRAE [36] captured the evolution of *plug load density*, defined as plug load-based electric consumption per square foot or square meters of office space. In the late 1990s, 1 W/ft^2 was published as the ASHRAE standard for the average density in medium-dense offices. For new offices, the ASHRAE Standard 90.1P [35] estimates density at 8 W/ft^2. Equipment density was also employed in [20], while a plug load density analysis was adopted in [4], discussing whether a rating system should be defined.

An individualized energy metric called Aggregated Power Index (API) is introduced in [39], which assists public sharing, aggregation and combination of energy use across different environments, and comparison among individuals. API is a combination of baseline and human-driven energy use.

Table 2
Benchmarks and KPI for MELs.

Metric/KPI/benchmark	Defined by	Description
ENERGY STAR [29]	U.S. DoE, U.S. EPA, industry	Power management to save energy
EU standby initiative [32]	European Commission	Energy efficiency of electric equipment when off or in standby mode
MELs usage factor [35,36]	ASHRAE	Ratio of measured wattage at nominal operating conditions to nameplate rating
Annual ICTs energy consumption [37]	Bristol City Council	Average energy consumption of ICT devices per year
Occupant plug load [38]	NBI	Provide a means to show occupants how their plug load usage compares to other like-type occupants and track performance
Plug load energy use rate [38]	NBI	The rate of energy use over a specified amount of time
Plug load density [36]	ASHRAE	Electric consumption of MELs per square feet or square meters of office space
Aggregated power index [39]	Taherian et al.	A combination of baseline energy use and human-driven energy us

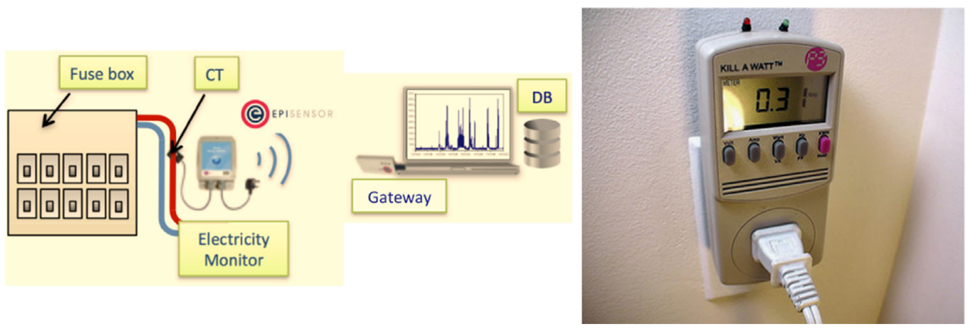

Fig. 3. Monitoring energy consumption of an office (left) and of an appliance (right).

A detailed review of existing benchmarks for small power in office buildings is conducted in [40]. According to the author, key metrics include details of power consumption and hours-in-use for ICT equipment. Table 2 summarizes the main metrics for describing the energy behavior and performance of MELs.

Our study indicates that numerous benchmarks and KPIs exist for green buildings and MELs, with each country having its own metrics, considering different parameters to characterize buildings according to their office equipment. Plug load density is a metric we came across multiple times while reviewing different initiatives [36,20,4]. Many metrics focus on the PM of ICT devices, especially when not in use, as this is admitted as an important source for savings [29,32]. We believe that benchmarking needs to be standardized worldwide, with well-defined and widely accepted performance metrics and KPI, such that people, organizations and governments can learn from each other, while global concrete goals for energy reductions in office spaces can be more easily defined.

5. Hardware for energy monitoring of office equipment

Energy monitoring is essential for understanding the sources of consumption inside a building, and to take appropriate measures to save energy. To perform energy monitoring, dedicated hardware needs to be deployed in the main electric distribution board, in specific branches/circuits or even on wall sockets to measure the consumption of individual electric appliances.

Originally, energy monitoring was based only on the traditional electric meter installed by the utility to measure the overall consumption. At this time, energy audits relied on log-books and calendars. Then, energy monitors appeared measuring the total consumption of the building in real-time. Popular commercial products include ZEM-30 Energy Monitor from Episensor [41] and TED Pro from TED [42]. Fig. 3a shows the installation for measuring the total building's consumption.

Even as recent as ten years ago, more sensitive meters were manufactured to perform sub-metering in specific branches or circuits of the building. Commercial products such as eMonitor from Power House Dynamics and FIDO from Ecodog became popular [43]. Nowadays, equipment for device-level monitoring is available by using smart plugs, smart power outlets and smart power strips. Smart plug strips are based on typical plug strip designs, but incorporate additional technologies to automatically disconnect power to equipment when not in use.

Most smart strips have one master control outlet, 4–6 controlled outlets that will automatically power down devices when the control load is turned off by the user, and 1–2 uncontrolled outlets that are always on. Commercial smart strip products are Isole IDP-3050 from The Watt Stopper [44] and Smart Strip SCG5 from BITS Limited [45].

Smart power outlets or smart plugs stand in between the wall socket and electric appliances to measure their consumption and control their operation. Fig. 3b shows the operation of a typical smart outlet. Popular products in this category are Energy Hub Socket from Energy Hub [46], Watts-Up? PRO [47], and Kill-a-Watt from P3 International [48].

In academia, various smart plugs have been developed to facilitate research in energy auditing. These devices offer actuation capabilities and may form wireless networks to propagate energy measurements to a base station. Examples include ACme sensor mote [49], used in many research works [50–53], MIT Plug [54], which is a functional power strip with sensing, networking and computing abilities, Synergy Energy Meter (SEM) from University of California, San Diego [55] and REAM [56]. Fig. 4 shows the ACme sensor mote. In these examples, the IEEE802.15.4 standard is used for wireless communication between the nodes of the network.

Nowadays, hardware products for energy metering are more stable and reliable, though their price is still high. This is the main reason load disaggregation techniques have been proposed (see Section 6). Some limitations of existing hardware are that it cannot sense the ambient environment (e.g. occupancy, temperature, noise), control of devices is limited to switching them on/off and

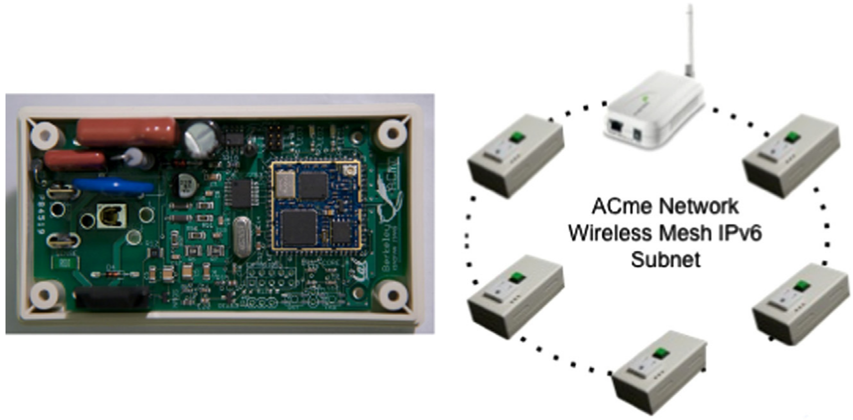

Fig. 4. ACme sensor mote device (left) and networking (right) [49].

also it fails to integrate smoothly with the rest electric appliances of the building (e.g. lighting, HVAC). Extra caution must be taken as these energy monitoring products, operating based on low-power wireless communication, might cause possible interference due to congestion in the local wireless network(s) of the building (e.g. Wi-Fi) [57].

Finally, we must also mention another category of hardware focusing on monitoring the power quality of MELs in offices [17,18]. These power monitoring or power quality devices observe the fitness of electric power to consumer devices, ensuring that the synchronization of the voltage frequency and phase allows electric systems to function in their intended manner without significant loss of performance or life [58].

6. Energy monitoring techniques

As Lord Kelvin said, "*if you cannot measure it*, *you cannot improve it*". It is difficult, if not impossible, to save energy without understanding the consumption patterns in an office space. Load disaggregation is important for evaluating and diagnosing the causes of energy wastage and for developing strategies towards specific energy reduction methods.

Recognizing device activity is a challenging task [59], since many appliances have similar current draw or multiple settings, operating in parallel with varied load and different cycles. Environmental noise makes the task even more difficult. A review of numerous efforts for load disaggregation is performed in [60], including an accuracy performance comparison.

Since it is expensive and time-consuming to measure each device/circuit in a building, non-intrusive appliance load monitoring (NILM) techniques were investigated to offer a simpler and less expensive alternative. NILM techniques basically apply a single, centralized instrument to monitor aggregated electricity consumption for a facility, which is disaggregated then into an individual circuit/device level from the overall signal. The general approach used is the following:

1. Generation of power/noise/other appliance signatures.
2. System training.
3. System validation.

In the next subsections, we illustrate the most important techniques for solving this task, dividing related work into supervised and unsupervised methods. The former case is when system calibration needs to be performed in parallel, i.e. the system needs to learn about the specific behavior of each device class. The latter case is when no calibration is required.

6.1. Supervised NILM techniques

The simplest and least expensive NILM techniques typically measure changes in real and reactive power levels, requiring only low frequency sampling [61,62]. More complex techniques rely on harmonic analysis to distinguish loads, requiring costlier hardware and sophisticated software [63].

In 1992, Hart [61] developed a NILM algorithm that determines the energy consumption of individual appliances based on state transitions, i.e. turning on/off. However, in case when load operates in multiple or variable states, NILM is difficult [59]. Laughman et al. [63] improved NILM by using event detection, to help disambiguate appliances with similar real/reactive power signatures. In [64], the load disaggregation algorithm differentiates edge cases with a classification of appliances according to their frequency of use to balance decision making. This approach had a limitation to a selected number of appliances with distinguishable differences in frequency of use.

As electricity in buildings typically flows along a tree-shaped distribution network, Jiang et al. [50] employed a sparse set of carefully placed 38 ACme wireless metering nodes [49] at several load sensing points to approximately disaggregate the active laboratory *load tree*, as he named it. The work in [11] presents a fast and effective heuristic clustering technique for extracting operating modes of MELs. Patel et al. [65] demonstrated a technique to detect and classify electric loads using a single plug-in sensor, by monitoring noises on power lines. Similar to this work, TinyEars [66] performs device-level power consumption identification primarily based on acoustic signatures of household appliances using audio sensors.

A fundamental limitation preventing wide acceptance of NILM, is its difficulty to calibrate an appliance recognition system ad hoc to each building typology. The RECAP system [59] tries to reduce this difficulty by using a single sensor clipped to main electric unit, guiding the user to profile electric appliances in order to generate a database of unique signatures. By using this signature database, RECAP trains an artificial neural network (ANN) system to recognize appliance activity.

6.2. Unsupervised NILM techniques

Unsupervised methods gained attention to reduce the effort needed to calibrate a system deployment for energy metering. ANNOT [67] automatically annotates appliance operating states

using inexpensive wireless sensors measuring heat, vibration, sound and light. Viridiscope [68] uses an array of indirect sensors such as magnetic, light and acoustic to disaggregate total load. NetBem [69] captures the contribution of networked business equipment to a power load via side-band detection of the equipment's operating state through the local area network.

Moreover, a proximity sensor is used in [70] to monitor energy consumption by individuals. The basic idea is that an occupant carries an active RFID tag, used for detecting proximity between a user and each device. Circuit-level energy monitoring combined with statistical Granger causality analysis is used in [71] to automatically understand the causal relationship between occupants and their energy use.

Finally, apportioning the total consumption of a building to individual users may provide incentives for reductions, as the users become able to understand their personal contribution to the overall expenditure of their office (see Section 8.4). The work in [72] suggests a simple technique to apportion consumption between users, according to user control and device ownership, while a more sophisticated method is discussed in [39].

Comparing supervised and unsupervised NILM techniques, the former are more accurate, with errors around 2–5%, while the latter are less accurate (5–15% errors), but much more practical and flexible. Most of the related efforts are not appropriate for large deployments in commercial buildings, focusing on residential environments having only tens of different loads with predictable signatures. Energy audits in offices are much more challenging. From the presented techniques, the authors believe that solely the works in [50,69,71] are suitable to be used for load disaggregation in office spaces. Still, true plug and play approaches for efficient NILM are inexistent and this is a challenging matter of future work.

7. Energy metering in office environments

Data at a macro scale is informative but difficult to act upon. It does not provide visibility into computing components that can be made more energy-efficient. While the energy bill offers useful first-level of information on identifying saving opportunities, it is difficult to identify specific gaps. Often, power data at a micro scale offers a greater deal of insight by characterizing every single device. Only when energy data is paired and looked against device utilization rate it becomes meaningful [3].

In general, the main research questions investigated during energy audits in offices are the following:

- What is the contribution of computing systems to the overall electricity consumption? How is this cost distributed across different components of the ICT infrastructure?
- Can we characterize the consumption patterns of office equipment? Are they used effectively or are there any gaps for energy reductions?
- How would one design a monitoring infrastructure to achieve good accuracy with the least effort?
- Which assumptions about power draw and utilization of computing devices hold in a general enterprise setting and which do not?
- Do devices of the same model or with same specifications have equal power draw or present variations?
- Do ENERGY STAR-labeled devices really use energy more rationally? Is it worth to invest in more energy-efficient equipment?
- Do employees make appropriate and efficient use of office equipment? Do they need any education or incentives for using office equipment properly? Which is the equipment density in units per employee?

Energy audits in buildings investigate both quantitative and qualitative aspects. The former is achieved through field measurements and monitoring as described in Section 6, while the latter is accomplished through online survey polls, questionnaires, and interviews with occupants and facility managers [20]. Various studies on energy audits have witnessed a wide range of plug load-based equipment, including ICT loads (e.g. printers, scanners, routers, servers) and non-ICT loads (e.g. coffee vending machines, microwave, refrigerators). Such diversity in office MELs often poses challenges for energy managers, auditors and energy modeling researchers. These challenges are explained in the work of Schoofs et al. [69].

Techniques for monitoring power loads are generally based on unique characteristics of electric appliances and cannot be easily applied to business equipment due to the low-power consumption of the individual devices. Low power means power footprints are similar to background noise and not recognizable.

7.1. Field protocols and methodologies

Monitoring and analyzing hundreds or thousands of plug load-based devices in a commercial building constitutes a complicated task. Intelligent field protocols and specific methodologies need to be developed, to perform the whole procedure as accurate as possible, involving equipment sampling, frequency of measurements, energy metering equipment to be used, etc.

A field protocol used to collect comprehensive data on MELs is presented in [73], based on a method for collecting device-level power data using small, relatively inexpensive wireless power meters. The authors claim that inventorying helps to compare the count and energy use between devices, while an energy breakdown shows that the ICT equipment offers the largest target for energy efficiency improvements in office.

Cheung et al. [74] investigated how to effectively inventory an office area, the fraction of inventoried devices to be metered, for how long and at what sampling rates. The work in [75] offers some interesting approaches to solve these issues, while the study in [3] offers insights into how combining power data, utilization statistics and metadata allows answering several questions about green computing like what is the contribution of ICTs to the overall consumption, and how this consumption is distributed across the various office equipment. In this aspect, PowerNet [52] takes a unique perspective by measuring not only device's power draw but also its usage.

7.2. Analysis and statistics

Insights from a massive study consisting of 455 wireless smart plugs and seven load-balancing routers across four floors of a commercial building for two years [75] revealed that annual ICT energy breakdown within MEL category is over 75%. Furthermore, measurements together with device inventory in [53] showed that approximately 56% of the total building's energy budget goes in computing systems.

From a study conducted in U.S. in 2004 [76], it was stated that about 74 TW h of energy per year is spent in ICT plug loads, of which the 71 TW h/year is spent in personal computing versus 4 TW h/year spent on networking equipment. This accounts for 2% of the total electricity consumed in the U.S.

A more recent study [7] identified 6–10 key plug loads across diverse commercial building types, and estimated their annual unit energy consumption in nine buildings. Another study performed in [4] revealed that the average plug load equipment

density for ICT equipment was about 9 devices/1000 ft^2 and 14 devices/1000 ft^2, totaling 23 devices/1000 ft^2. PCs may take 50% of the electricity footprint of ICT equipment, while ICT-related services (e.g. servers, routers) are responsible for 30% of the total energy consumed in an office [37].

Finally, a better understanding of the diversity and density of typical MELs used in offices was studied in [77]. This study offers insights into the operation of MELs and the user interaction with them in an everyday setting, based on an analysis of power and time-of-use data recorded from more than 400 office electronics in California offices.

7.3. The importance of power management

Several audits [78,12,79] have demonstrated that PM is an effective means to save energy, especially during off-work and night-times. PM reduces consumption of computing devices by slowing the clocking rate, powering down certain sections of the hardware and spinning down the hard drive.

Computers, monitors, or printers are dynamically hibernated to save energy. The low-power states of computers can be configured by the user and kick in when a host is idle for a critical time period. The Advanced Configuration and Power Interface (ACPI) specification [80] defines four different power states that an ACPI-compliant computer system can be in. These states range from G0-Working to G3-Mechanical-Off. The states G1 and G2 are subdivided into further sub-states that describe which components are switched off in the particular state. PC Energy Report 2009 [81] quantifies the effect of PM by commenting that if 17 million UK workers turned off their computers regularly at nights, this would reduce CO_2 emissions by 1.3 Mtons, equivalent to removing 245,000 cars off-road.

In southern Africa, a series of five audits on offices found that 56% of total building energy was consumed in non-working hours [79]. Based on NetBem [69], the authors in [82] have performed an extensive experiment within a University department (schools can be parallelized to offices), discovering that 10% of regularly used client machines were constantly powered on, 68% had night-time activity and 53% weekend activity. They observed that 38% of machines have exhibited clear patterns of electricity wastage at night-time, representing 5–6% of the school's total consumption, and 35% of machines have exhibited clear patterns of electricity wastage during weekend days, representing 12–15% of the school's consumption. Their approach is very promising, and can be depicted in Fig. 5.

In 2001, Webber et al. [78] estimated potential PM savings of 56% and 96% for monitors and printers respectively, based on a walk-through audit across 10 buildings covering 100 devices per site. Another study [12] observed that PM settings alone could save 23 TW h/year, while when these settings are saturated effectively they can save 17 TW h/year, and with night-time shutdown additional 7 TW h/year, in U.S. offices alone.

A complete study performed by the International Energy Agency (IEA) [6] indicates that for a typical PC user profile, the ability to automatically enter into low-power mode when not being actively used can cut electricity consumption to half.

Finally, Kazandjieva et al. [3] suggest that ENERGY STAR data should be used cautiously. It is composed entirely of devices that

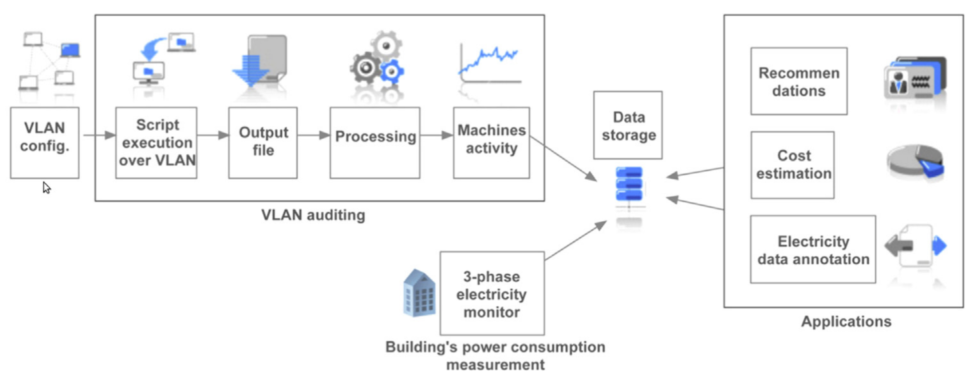

Fig. 5. The NetBem algorithm (Source: [69]).

Table 3
Methodologies and key findings of related work in energy audits in buildings.

Authors	Year	Building	Methodology	Key findings
Kazandjieva et al. [3]	2012	University campus	Use of PowerNet infrastructure [52] to study relation of power consumption and MELs	54% of building load for computing of which 30% to server, 16% to PCs and 7% to displays
Dawson-Haggerty et al. [75]	2012	School and office	90,000 ft^2 buildings, field deployment of 500 ACme sensors, stratified sampling and staged metering	Energy consumption of ICTs is over 75% of MEL category
Kazandjieva et al. [53]	2010	University campus	Use of device inventory and PowerNet infrastructure [52] to measure power consumption	56% of total building energy budget goes in computing, at a cost of $22,000 per month
Kawamoto et al. [76]	2004	Office	Surveys and field measurements of usage in business hours and turn-off rates at night	74 TW h of energy per year spent in ICT plug loads, 71 TW h/year in PCs, 4 TW h/year on networking
Webber et al. [4]	2006	Health centers and offices	After-hour power state of ENERGY STAR-rated office equipment	Equipment density of 9 plug loads per employee
Schoofs et al. [82]	2011	University and residential	Side-band detection of network equipments operating state through LAN	10% client machines constantly ON, 68% night-time and 53% weekend activity
Webber et al. [78]	2001	Multiple building types	Walk-through night-time audit, PM settings and turn-off rates	44% computers, 32% monitors, 25% printers turned off at night
Kawamoto et al. [12]	2002	Residential, commercial and industrial	Annual unit energy consumption estimate based on stock, power requirements, usage and saturation of PM	Total office consumption in U.S. is 74 TW h/year, PM can save up to 40 TW h/year

have passed minimum energy efficiency requirements, some data is self-reported, and it does not reflect thoroughly the distribution of devices sold. Furthermore, ENERGY STAR measurements and certification do not consider PCs under load, they only deal with on/off and sleep states.

A summary of the most important case studies dealing with energy audits in offices, including the methodology used and their key findings, is summarized in Table 3. Energy audits suggest that office equipment constitutes an important source of consumption in commercial buildings, being responsible for 30–50% of total consumption [53,37]. The works in [73–75] offer valuable advice for the deployment of energy metering equipment in offices, discussing critical tradeoffs that need to be considered. Finally, this section discusses the significance of PM as a key factor for energy savings. The efforts in [82,78,12,6] suggest that savings can reach more than 50% with proper PM adjustments.

8. Measures for reducing consumption of MELs in offices

In this section, we list popular methods for reducing the consumption of plug loads in offices, focusing mostly on ICT equipment. Office spaces have wide variance in plug load power densities, equipment types and policies on allowable equipment, shutdown and hibernation. Therefore, energy saving strategies need to be tailored specifically to each space, for maximum impact. In general, the following methodology is adopted for measuring, analyzing and reducing plug loads [83]:

1. Establish a technical team to develop a business case.
2. Benchmark current office equipment and operations.
3. Measure the loads by selecting the most appropriate metering technology.
4. Identify occupants' true needs and tradeoff between their needs and overall efficiency.
5. Promote occupants' awareness.
6. Reduce MELs consumption through control strategies and design decisions.

Measuring the loads is a key step, and it can be performed by the hardware presented in Section 5 and the techniques listed in Section 7. An accurate metering would then facilitate the development of strategies for reducing these loads. In the next subsections, we focus on the final step from the list above (6), related to electricity savings through control strategies and design decisions, discussing various approaches classified in the following categories: software-based techniques; hardware-based methods and management systems; suggestions and advice; and ways of affecting the occupants.

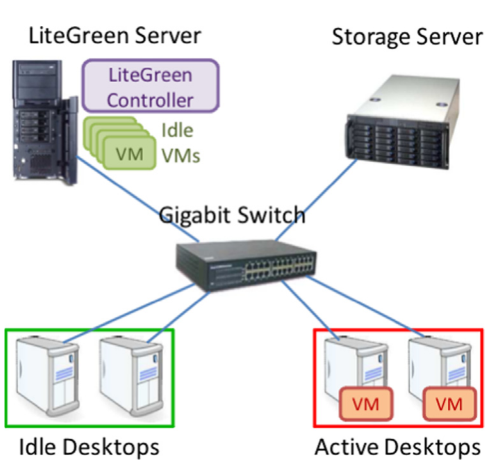

Fig. 6. The concept of LiteGreen (Source: [95]).

8.1. Software and applications

Software measures include setting equipment to optimize operation (e.g. brightness of monitors, operating mode of computers) or using power management software on computers [84].

8.1.1. Power management

Concerning computer operating modes, Wake-on-LAN technology [85] has the ability to wake-up sleeping systems by sending to them specially coded network packets. Hence, systems do not need to be on (e.g. during the night), but can be in sleep-mode to save energy, and still be able to respond to network requests when needed.

Somniloquy [86] is an architecture exploiting this feature, demonstrating through a case study energy savings of 60–80% in commonly occurring scenarios. Following a similar concept, SleepServer [87] is a system enabling hosts to transition to low-power sleep states, while maintaining their applications' network presence using a proxy server. Measurements show similar savings for PCs, ranging from 60% to 80%, depending on their use model. However, in a real-world enterprise setting, this approach achieved energy savings of about 20% [88], questioning the previous optimistic predictions [86,87].

Kawamoto et al. [76] argue that PM systems can reduce the equipment's power usage cost between 20% and 30%, by shortening the power saving delay time from 60 to 15 min.

Commercial products dealing with PM include Faronics Power Save Enterprise application [89] and Cisco's EnergyWise [90]. The former creates custom settings to schedule and enforce when a computer goes into power saving modes, while the latter controls office equipment powered over Ethernet, for example it can monitor the consumption of routers and switches as well as manage the power consumption of IP-phones during low usage times, powering them up when in high use.

8.1.2. Virtualization

Virtualization takes several physical servers and consolidates them onto a single piece of equipment, reducing the amount of hardware that needs to be powered and maintained. Server management services reduce energy consumption through improved hardware utilization and by automating server maintenance procedures [91]. Commercial products include VMware Horizon View [92] and Parallels VDI [93].

A virtualized office environment is proposed in [94]. Office hosts are virtualized and virtual desktops are created dynamically on office hosts. Possible savings of about 50% are reported with this approach.

LiteGreen [95] is a software aiming to save energy by virtualizing the desktop environment as a virtual machine, and then migrating it between the user's physical machine and a virtual server, depending on whether the PC is being actively used or is idle. Thus, the user's desktop environment is always on, maintaining its network presence even when the user's machine is switched off saving energy. This seamless operation also allows LiteGreen to save energy during short idle periods such as coffee breaks. The concept is illustrated in Fig. 6. Findings from a small-scale deployment comprising over 3200 user-hours of the system show that LiteGreen helps desktops sleep for 86–88% of the time, with energy savings of 72–74% with LiteGreen compared to 32% with existing Windows and manual PM.

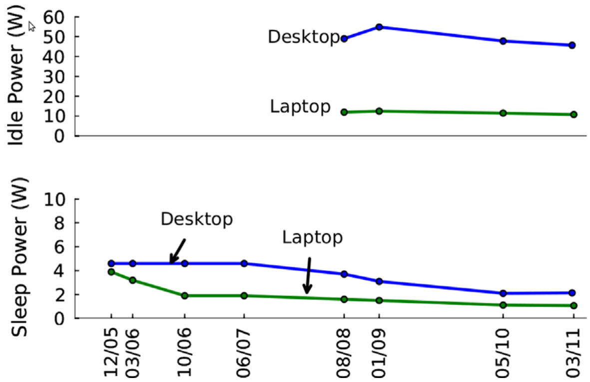

Fig. 7. Evolution of idle (top) and sleep (bottom) power for ENERGY STAR-qualified desktops and laptops (Source: [5]).

8.1.3. Others

Other techniques include the replacement of energy-consuming office hosts by highly energy-efficient *thin clients* [96], improving TCO and reducing consumption. Examples include the LINUX Terminal Server Project [97] and Citrix XenApp [98].

A popular range of applications targeting electricity savings include live, online visualizations of office energy use. A review of various visualization software products is provided in [99]. Most popular are the BuildingOS and Building Dashboard from Lucid [100], Pulse Product Family from Pulse Energy [101] and IntelliFace from Quality Attributes [102].

Regarding ENERGY STAR, calculators of ENERGY STAR-qualified products are available in [103], estimating the annual dollar and energy savings you can expect by installing an ENERGY STAR-qualified device. ENERGY STAR Portfolio Manager can be used for measuring and tracking energy consumption, as well as greenhouse gas emissions [28].

8.2. Hardware and systems

Hardware-based techniques employ energy monitoring and control of MELs (see Section 5), in order to reduce consumption. Management systems include (usually tailor-made) software and hardware applied for the automation of ICT equipment such as computers, servers and routers, with the goal of reducing electricity consumption as well as human interaction for maintenance and management.

8.2.1. Smart plugs and plug strip interventions

Acker et al. [104] provide findings from a two-year project to characterize space level plug load profiles and explore load reduction interventions. Average savings of 0.6 kW h/ft^2/year were found by plug strip interventions with occupancy sensors, and 0.76 kW h/ft^2/year from ENERGY STAR equipment upgrades. The report in [84] builds on the findings of the field metering study conducted in [77], identifying some effective hardware measures such as installing timer plug strips on printers and monitors, replacing desktops with laptops and replacing inefficient devices with the ENERGY STAR ones.

Furthermore, the study in [10] addresses the energy efficiency of MELs in IT office buildings in India and U.S., using load monitoring and control devices such as smart plugs. Smart plugs are used to control the operating schedule of MELs based on pre-programmed user input, which is typically based on timing, usage and company policies. The authors suggest a master/slave-type control mechanism in which power states of primary devices (like PCs) will dictate power states of their logically grouped devices (like speakers, monitors, printers).

The Green Proving Ground program [105] assessed the effectiveness of power strips by monitoring more than 295 devices across eight office buildings for four weeks. Results indicated that the use of cheap scheduled timer controls yielded reductions of 43% from baseline, whereas combining load sensing and control offered only 23% savings, and is best suitable for individual workstations where occupants have various appliances and unpredictable schedules.

A pilot study is reported in [106], where data from a variety of plug loads were collected in NASA Ames campus, to understand usage patterns and make an assessment of the effectiveness of controlling (e.g. turning on/off) selected loads. Findings indicate that choosing energy efficient equipment, ensuring that power saving functionality is operating effectively and employing plug load controls to turn off equipment when not in use can lead to significant energy savings. Finally, the factors affecting hardware efficiency for general-purpose office electronics are explored in [35], together with the future intensity of usage for major types of input/output equipment. In a similar study [36], recommendations are provided, allowing engineers to make better decisions on office hardware taking into account its energy consumption.

8.2.2. Replacing equipment

Reducing or replacing the amount of physical equipment can help to save energy. For example, centralized printing devices can be used to replace individualized printers per employee [107]. Dell saves 40% by using more efficient PCs for its workforce [81]. Intel IT [108] is reducing office power consumption by evaluating and implementing enabling technologies and by changing business practices.

In general, there is a growing use of laptops as replacement for desktops [4]. Kazandjieva et al. [5] suggest that it is far more cost-effective to replace desktops with docked laptops, rather than deploy software solutions to manage desktop energy. Calculations show that, over three years, replacing a desktop with a laptop can save on average $300, over 80% of the energy cost and 32% of the total TCO. This study proposes that laptops are more efficient than thin clients too.

A comparison between ENERGY STAR-qualified desktops and laptops, in terms of the power consumed in idle and sleep mode is shown in Fig. 7. Moreover, power consumed by monitors varies by technology with the typical LCD screen drawing one-half to one-third of the power of an equivalent-sized CRT monitor [6].

8.2.3. Hardware vs software

On the debate *hardware vs software*, it seems that hardware efficiency is more important than software solutions, both from an energy and economic perspective. Hence, influencing purchasing is more effective than adding complexity on top of existing systems.

What happens when software-based energy-saving techniques are applied to an already hardware-efficient computing infrastructure? Even though the percentage of energy reduction could be high, up to 60–80% for the previously mentioned approaches [86–88], the absolute dollar savings will be low. For example, applying LiteGreen [95] on top of an ENERGY STAR-qualified laptop saves $8.50 a year per machine and $12 for the empirical enterprise measurements performed in [5]. This means that if the software requires more than 15 min of attention from the IT staff, or harms a user's productivity by more than half hour, the savings may not be worthwhile.

8.2.4. Connecting to the smart grid

A smart grid describes the future electricity grid, enhanced with ICTs for more intelligent behavior. Commercial buildings have

a key role in the optimized operation of the grid, in programs such as demand response (DR) and load shedding. A system dealing with DR situations through user-specified actuation policies is presented in [55], geared towards managing plug loads. An algorithm showing how distributed metering can be leveraged in automated DR is introduced in [109], supporting selective deactivation of devices within a group of buildings rather than turning on additional power plants to meet the peak demand.

Microgrids constitute islands of small smart grids, consisting of energy generation sources and storage, connected to a group of buildings consuming electricity. The work in [110] examines the important role that buildings play in energy management in a smart microgrid. By installing energy measuring equipment at a university campus, the authors discuss the relationship between ICT equipment and energy usage, showing that control of ICT subsystems can lead to significant savings.

8.2.5. Combining sensing with actuating

Automating some building operations towards energy savings many involve both sensing and actuating. Sensing includes energy metering but also ambient context awareness such as occupancy and illumination in the offices. Actuating is about switching on/off various MELs, or changing their mode of operation. Weng and Agarwal [111] discuss how to design smart buildings focusing on the central role of actuation within them. Jiang et al. [50] mention some potential approaches for sensing relevant parameters like temperature, flow and occupancy.

Location data collected over 60 days in a commercial environment are used in [112] to evaluate the savings potential. The findings showed that 75.8% of the average user's working day is spent in his office, and that around 140 W h/PC/day could have been saved, compared to a policy that has machines on for the whole working day.

8.3. Suggestions and advice

There is a plethora of related work offering advice on savings on MELs. We present some comprehensive reports in the area.

At first, Bristol City Council has developed a green ICT database to assist organizations with reducing their carbon emissions from ICT [37], discussing numerous ideas for saving energy. A report by the National Renewable Energy Laboratory, U.S. Department of Energy (NREL) [83] offers a self-answered questionnaire to help the owners perceive the potential for savings in their buildings, providing an overview of plug loads based on long-term studies, suggesting strategies to building owners, managers and occupants to reduce these loads.

Furthermore, options for energy conservation according to the operation modes of ICT devices are discussed in [14]. Mohanty [113] reviews estimates of standby power losses in different countries, analyzing various techno-economic options to reduce standby power consumption. Policy instruments and approaches adopted to tackle this issue are listed and some country-level initiatives are highlighted.

A document by RISO [114] talks about how to accurately read the specification labels of printers and copiers, so that users can calculate their energy consumption needs and select the best suited model to their needs. Interestingly, most printing devices consume in aggregate more energy while in standby mode than if they were printing the whole day. Standby mode in printers/copiers keeps the fuser warm and ready for printing, in contrast to sleep mode that puts the fuser off, operating in a relatively low-power mode and taking more time for warming.

Strategies for plug load reductions are proposed in [15], calculating potential reductions per strategy. Finally, guides for best practices in managing consumption of office equipment are included in [115,116].

8.4. Affecting the occupants

The actions of the occupants affect significantly office consumption, by controlling ICT equipment such as computers and printers, controlling task lights and in some cases the thermal environment via thermostats, fans and heaters, shades and/or windows. It has been estimated that 20–50% of total building's energy use is controlled or impacted by occupants [81,117].

It is important to consider that employees are demanding that their organizations should become more sustainable, willing to embrace workplace sustainability [118]. As green becomes more mainstream, a growing number of employees want to work for a company committed to sustainability [119]. Hence, it is important to motivate occupants to engage in energy-saving actions and sustainable lifestyles.

8.4.1. Behavioral/psychological studies

An interesting study aiming to understand the incentives of office occupants not saving energy at work is presented in [120]. A field trial was conducted over 22 weeks involving 83 office workers in a university, providing them with continuous personal feedback on energy use. Various reasons for increased use of electricity have been identified, explained by a lack of positive goal or motive to drive energy reduction behavior. Overall, a reduction of energy use was found at the third and fourth months of the study.

Two simple interventions were evaluated in a research center in [121], reinforcing the findings of the previous study about the positive effect of frequent eco-feedback. The first involved group-level feedback presented monthly to employees via e-mail. The second used peer educators to disseminate information and to encourage colleagues to reduce energy use. Both interventions were compared to an information-only control designed to educate employees about how and why to conserve energy. Results indicated that feedback and peer education resulted in a 7% and 4% reduction in energy use, respectively. Buildings that received the control increased energy use by 4%.

Competitive situations between employees may further motivate them. The study of Siero et al. [122] shows that people achieved more energy savings when they were provided with comparative information on energy consumption. In regard to rewards, Foster et al. [117] found that office workers would prefer monetary values to engage in energy-saving programs. Fogg [123] discovered that occupants would prefer realistic and tangible rewards rather than the virtual ones.

Engaging the employees directly to understand how their actions can contribute to achieving environmentally superior performance is discussed in [124]. Implications of using social media for improving communications between building occupants and operators are explored in [125].

8.4.2. Commercial approaches

In line with the previous findings on the positive effect of eco-feedback, a study by Intel [108] showed that employees who were provided with energy and cost information reduced their energy usage by more than twice the one of employees who installed power management software, but were not provided with energy usage information.

A modern idea for influencing employees towards sustainability is the concept of *Green Teams* [119], defined as self-organized, grassroots groups of employees who voluntarily come together to educate, inspire and empower other occupants, implementing

solutions to help their organizations operate in a more environmentally sustainable fashion.

CarbonRally [126] is a Web-based activism platform that challenges users to reduce their personal carbon footprints. Participating employees are able to make individual pledges for energy reductions in their work environments. Regarding commercial products, Greentrac Incite [127] provides online, real-time feedback and uses various incentives to motivate employees to implement energy-saving measures. According to Greentrac, involving employees in energy-saving campaigns can lead to a 30% increase in efficiency over automated shutdown power management strategies. AngelPoints [128] is a platform that helps an organization mobilize the collective power of its employees to make a positive impact.

There is a disagreement on whether to involve employees in energy-saving initiatives or to invest in building automation. Marchiori et al. [129] conclude that automation is necessary to ease the more tedious tasks such as *unplug when not in use*. However, employees may find automated interventions unfavorable, even going to extremes of circumventing them when they impact their daily work tasks [117]. Providing end users with the flexibility and capability to implement savings tends to be effective. Perhaps the model that will likely perform best is a combination of automation and end-user behavior.

8.5. Discussion

As we saw in this section, energy reduction efforts are divided in two broad categories: software and hardware-based. Software-based techniques consider mainly PM and virtualization. Somniloquy [86] and SleepServer [87] are pioneering efforts regarding PM, claiming significant savings exceeding 60%. LiteGreen [95] and VMware [92] are dominating in the field of virtualization. Current commercial products for PM and virtualization are efficient and reliable, offering advanced features and large potential for savings.

Hardware-based approaches focus on involving physical equipment such as smart plugs and smart plug strips for controlling ICT devices. The studies performed in [105,84,106] indicate the perspective of considerable savings. In addition, replacing equipment with more energy-efficient can be effective, as observed in [81,5], with savings around 40–60%. Our point of view is that the contribution of hardware-based methods for savings needs to be *quantified*. In this way, companies and organizations would be aware about the return of investment when considering any of these approaches.

A comparison among software- and hardware-based techniques [5] shows that hardware-based approaches are more effective, for example by replacing desktop PCs with laptops. Other approaches stress the role of commercial buildings in smart grid scenarios [110,55] and the importance of combining sensing with actuation [111].

Finally, relevant efforts recognize the large impact of occupants, affecting 20–50% of total building's energy use [81,117], and focus on motivating the occupants towards energy savings through suggestions and advice, timely and comparative eco-feedback techniques [120–122]. We highlight the study by Intel [108], claiming that employees who received timely feedback reduced their consumption by more than twice the one of those who installed PM software. We believe that the role of occupants is still underestimated, and future efforts need to study more specifically the influence of users on energy consumption, exploring how various persuasive strategies can help them to acquire more energy-saving lifestyles.

9. Open issues – future challenges

Through the process of studying and evaluating state of the art work in this domain, we have identified various open issues and future challenges that need to be addressed by stakeholders, key players and researchers. We list these issues below:

1. Most related work involves case studies covering only several months, using limited measuring equipment. Measurements need to include a large and diverse number of devices for longer periods [3]. The lesson is that a small sample is not desirable if trying to extrapolate to a large, heterogeneous set. Examining the monthly average power draw of each machine reveals that no single month is representative of the whole year. Measuring numerous devices allows us to characterize the variation of power draw and utilization across and within device types. If research in green computing continues to rely on short-term field measurement studies, we risk using limited and possibly outdated data to evaluate new systems.
2. In regard to energy audits in commercial buildings, load disaggregation based on a single sensor or only a small number of sensors is still a challenging issue, due to the hundreds of low-power loads existing in office environments [69,71,50,60]. It would be helpful to develop reliable methods to identify and measure mobile devices (e.g. laptops, chargers) and devices that move between power outlets inside the building (e.g. fans, heaters). Though the energy each mobile device consumes is relatively small, as new technologies are adopted by millions of consumers, understanding the cumulative effects of their use on electricity consumption becomes important [130].
3. Smart electronic meters can only measure power consumption of ICT equipment but not indicate its functionality or device usage [52]. Determining operating modes is important for better analysis and characterization of overall consumption [78,12,79]. In relation to this, the load profiles for most devices are still poorly understood [104]. Thus, there is a need to explore load duration curves of key plug loads in different regions and building types, to better map how usage patterns affect consumed power. Moreover, understanding the electric load patterns of distributed, shared IT resources can help in automating DR management in peak load scenarios [110].
4. Our observations show that MELs are not very smart in terms of energy savings, though many are covered by an ENERGY STAR specification. It has been observed that ENERGY STAR labeling is predominantly used as a regulatory mandate for only desktops, laptops and monitors under the ICT device class [6]. There is still a large potential of savings [53,78,76,106,79,73], and manufacturers need to push more intelligence in components, equipment and services. Power sensing and communications could be built into devices to enable them to cooperatively manage their aggregated power state for minimizing energy use, e.g. by virtualizing their resources [95,94].
5. Sensing the office environment and collecting additional data, beyond energy and power, for example occupancy, illumination and noise, offers many opportunities for savings [111,50,112,73]. By augmenting datasets with metadata including network device registrations, utilization statistics and explicit equipment inventories [69–71,82], this would allow us to answer several open questions about green computing. Augmented data is key in determining energy waste, especially in cases when power is drawn but no useful work is done.
6. Section 8.4 shows that occupants play a critical but poorly understood and often overlooked role in the building

environment. There is a large variation in electric energy demand even in nominally similar buildings [81,117]. Questions such as how to influence users to use office equipment more rationally and how to affect them to become more energy-aware are still open [117,123]. Personalized behavioral strategies such as the ones in [120–122] need to be further studied and the factors and incentives affecting user behavior need to be better understood.

7. Privacy is an important matter when developing a long-term energy audit. As Sintoni et al. demonstrated [131], it is possible to learn about occupants' activity within a building without their knowledge, only by monitoring their overall consumption. In addition, statistical methods can reveal a range of private information, such as how many people are in the office and their routines [132]. There is a need to respect the privacy of occupants and avoid exposing details about their habits or lifestyles.
8. While there is an emerging consensus about the key approaches for achieving energy efficiency in buildings, the potential impact on energy reductions of various techniques is not sufficiently known [133]. Companies do not know in a tangible way the amount of money they would save by adopting a particular technology, incremental costs or the payback period of their investment. Furthermore, the energy used by ICTs and the energy efficiency induced by ICTs have been studied almost independently so far. Most studies fall short of conceptually contrasting own consumption of ICTs and the energy efficiency they can induce across society [134].
9. Current building modeling software applications use static models with pre-determined parameters to model energy, instead of realistic sensing data. Hence, they cannot model appropriately appliances, end-utility points, and occupants' behavior, and the simulation results exhibit low fidelity. Software developers could exploit the vast collection of measurements acquired in related projects (see Section 7), to build more realistic energy models.
10. This enormous collection of plug load measurements could be used to create an online database of appliance signatures. In this way, research involving pattern recognition and load analysis/disaggregation would be facilitated, while companies would gain a better picture on the realistic consumption of their equipment. The general concept of a collaborative energy encyclopedia was proposed in [135], but not adopted by the public.
11. Since each case study employs different metrics, making comparisons of total energy use across studies is a challenging task. Although Section 4 discussed some benchmarks for green commercial buildings in regard to MELs [25,35–38,26,4], there does not yet exist a standardized and cohesive framework for evaluation and assessment of buildings in terms of energy savings and sustainability, including objective building performance metrics [4,26] and key performance indicators [38,27]. Apparently, a common ground needs to be defined, including evaluation metrics as well as a universal plug load taxonomy, easily expandable to include new devices and technologies as they come to the market.
12. Finally, although this topic has not been covered in this paper, another major issue that must be faced is the maintenance of the power quality within acceptable limits [17,18]. MELs are now sharing the building's wiring system with electronic lighting, HVAC, and various office equipment. While this type of equipment increases productivity, it can often be adversely affected by poor power quality. Building designers and engineers, as well as office equipment manufacturers, need to consider this issue more seriously as the number of MELs increases steadily in commercial buildings around the world. Some basic measures include equipping the buildings with power-quality devices [58] and incorporating power-factor correction circuits into the power supplies of MELs.

10. Conclusion

In this survey paper, we have illustrated the importance of energy conservation on MELs, and presented prominent efforts on techniques to measure the energy consumption of plug loads and approaches for savings.

To make our study more comprehensive, we have identified related works on the taxonomy of MELs, benchmarks and metrics used to characterize these loads towards greener buildings, and also listed particular devices and techniques for energy metering and load disaggregation. Through our review, twelve areas were identified in which future work needs to focus, in order to better monitor, characterize and analyze office equipment.

Our findings revealed that MELs are underestimated as a potential source of consumption, while this proves to be wrong. While research has mainly focused on conserving energy in lighting and HVAC, the consumption due to plug loads tends to largely increase.

It is probably not realistic to rely on commercial buildings to suddenly replace existing MELs with *best-in-class* or to reduce building's consumption through automated controls [7]. Changes towards green behavior are expected to come progressively, when stakeholders realize the importance of investing in the efficiency of their office equipment.

While hardware- and software-based techniques can affect electricity consumption in a large degree, provisioning is crucial for conservation. Decisions made during the early design stage can influence about 60% of total energy usage life cycle, leaving the impact of user behavior and real-time control to the rest 40%. Still, even small savings can have significant effects on the overall costs of companies and on the environment.

Apparently, in order to achieve standardized, effective and objective green standards for commercial buildings and MELs, international energy policies and regulations need to be defined by stakeholders and key players, involving legislative measures, economic instruments, voluntary agreements and technology and innovation specifications.

Finally, embedded ICTs, although increasing their collective energy consumption globally, are expected to play a crucial role in energy efficiency across the economy, helping office equipment to operate in a more intelligent, automated and efficient way.

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